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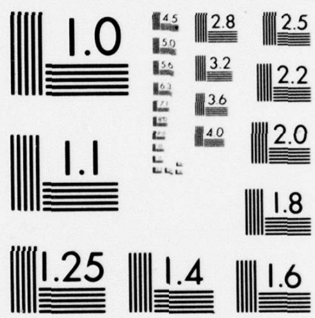

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Final Scientific Report

on

Analysis and Design of Composite Bonded Joints Under a Dynamic Type Load

Jack R. Vinson
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
UNIVERSITY OF DELAWARE
NEWARK, DELAWARE
AUGUST 1978

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This ~~Reports~~ discusses the results of four years of work under the referenced grant. Principal effort was in the title area, with some work in these subsidiary areas: response of spherical and cylindrical shells to localized loads, determination of interlaminar shear and normal stresses in laminated composite shells, the analysis, design and optimization of bonded joints in composite constructions; including the determination of shear properties of promising adhesives, review of the state of technology in mechanical fasteners in composite structures, and the response of many constructions to hygrothermal loadings.

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AUGUST 1978

Research Sponsored by the

Air Force Office of Scientific Research

Washington, D. C.

FOREWARD

This final report is prepared for the Air Force Office of Scientific Research, and completes Grant AFOSR-74-2739. This research was conducted under the technical monitorship of Mr. William J. Walker.

The support of this research is gratefully acknowledged and appreciated.

ABSTRACT

The enclosed reports the results of four years of work under the referenced grant. Principal effort was in the title area, with some work in these subsidiary areas: response of spherical and cylindrical shells to localized loads, determination of interlaminar shear and normal stresses in laminated composite shells, the analysis, design and optimization of bonded joints in composite constructions; including the determination of shear properties of promising adhesives, review of the state of technology in mechanical fasteners in composite structures, and the response of many constructions to hygrothermal loadings.

Table of Contents

I. INTRODUCTION

The purpose of this research was to find solutions to problems of composite material structures which are important, timely, and necessary to make significant steps forward in the growing technology involving composite materials utilization.

The research has been focussed primarily on methods of analysis for bonded joints in composite materials structures, but other problems have also been studied such as localized loads on composite shells, interlaminar stresses in composite cylinders, shear mechanical properties of promising adhesives, and hygrothermal (combined high temperature and high humidity) effects on structures utilizing composite materials.

II. SUMMARY OF RESEARCH PROGRESS

The research associated with this Grant can be divided into six distinct problem areas. Each is an important facet of major problems associated with using composite materials in aerospace structures. The research in each area will be discussed in some detail below.

A. Stresses in Spherical and Cylindrical Shells Subjected to Lateral Loads

The actual research in these areas was performed under the previous Grant AFOSR-69-1760, but the actual publication of the results occurred during this reporting period. Hence, this is discussed herein for completeness.

Accurate methods of analysis were developed for the bending and membrane stresses as well as deformations in thin circularly

orthotropic, shallow spherical shells subjected to a static localized loading at the apex. To insure that the results are applicable and accurate for shells composed of fiber or whisker reinforced composite materials, transverse shear deformation effects are included in the thin shell theory. Over and above the methods being applicable to shells of composite materials, merely letting the properties become transversely isotropic the methods apply to shells of pyrolytic graphite and its alloys. Moreover, letting the properties become isotropic and retaining transverse shear deformation effects, the results are in close agreement with previously obtained results of Rosettos for isotropic sandwich shells; and if transverse shear deformation is removed, the methods provide results in very close agreement with the results previously obtained by Reissner for thin isotropic single layer shells.

The technique of solution includes reducing the governing differential equations to a single second order complex differential equation. The solutions for stresses and displacements are in terms of modified Bessel functions of non integer order and complex argument, which are in turn transformed into a set of nondimensionalized, rapidly converging infinite series. The methods developed are the first to include combined effects of orthotropy, transverse shear deformation and concentrated loadings on spherical shells.

Over five hundred cases were calculated by digital computer using the analytical solution to see the effects of various material and geometric parameter variations.

The results of this research were presented at the Third International Congress on Space Technology in Rome, and at the ASME Pressure Vessel and Piping-Nuclear-Materials Conference in Miami in June 1974. It was also presented in seminars at Ohio State University and at the Eidgenossissche Technische Hochschule, Zurich. The research was published as a Ph.D. Dissertation of Howard S. Kliger, as two AFOSR-Technical Reports, and published in the ASME Journal of Pressure Vessel Technology in November 1974.

Accurate methods of analysis have been developed for bending and membrane stresses and deformations in thin orthotropic cylindrical shells subjected to static localized lateral loads. Not only are the methods of analysis applicable to cylindrical shells of composite materials, but analogous to the methods developed for spherical shells, they also can be used to investigate transversely isotropic material shells such as pyrolytic graphite and its alloys, and shells of isotropic materials. In the latter the results are identical to those developed previously by Bijlaard. These methods are the first to include combined effects of orthotropy, transverse shear deformation and concentration loads on cylindrical shells.

The governing differential equations were developed, and transformed into a set of algebraic equations through expanding all dependent variables in a doubly infinite series in the shell coordinate system. A digital computer program was formulated to perform numerical calculations for design and analysis purposes. Design curves have also been developed for large variations in anisotropy which blanket all known composite materials and isotropic

materials. Design curves and tables can be used directly in design.

The results of this research have been published in an AFOSR Technical Report, in Section 7.4 of a textbook "Composite Materials and Their Use in Structures", and presented at the 12th Annual Meeting of the Society of Engineering Science, Austin in October 1975.

B. Interlaminar Stresses in Laminated Cylindrical Shells of Composite Materials

Accurate methods of analysis were developed for stresses and deformations in a laminated circular cylindrical shell composed of generally orthotropic materials subjected to arbitrary axially-symmetrical mechanical loadings. A theory of elasticity solution for thin shells including transverse shear deformation was used in this derivation. By treating each lamina individually in conjunction with stress and displacement boundary conditions at the interfaces between laminae, the equations for individual laminae can be combined, yielding the interlaminar stresses as dependent variables which are then solved for explicitly.

The results are also presented in the form of a parametric study explicitly for a generally orthotropic circular cylindrical shell composed of both two and three laminae, subjected to a uniform lateral pressure for both clamped and simply supported boundary conditions. The solutions obtained also provide much insight into the interlaminar stress fields of shells of all shapes with any number of plies and the solutions also provide an excellent check-point or baseline for finite difference or finite element

computer solutions for the same problem.

The results of this research are published as a Master's Thesis of Terence L. Waltz, published in an AFOSR Technical Report 75-1629, presented at the 16th AIAA/ASME/SAE SDM Meeting, Denver, May 1975, and published in the AIAA Journal, September, 1976.

C. The Analysis and Design of Composite Material Adhesive Bonded Joints under Static and Fatigue Loadings

As stated above, the primary thrust of this research program has dealt with the very important problem of the analyses and design of adhesively bonded joints in composite materials structures. Many aspects of these important problems have been studied in depth.

To more clearly understand the many parameters which influence the static and fatigue capabilities of composite material adhesive bonded joints, a comprehensive analytical program was conducted. The motivation was that because of a lack of sufficient knowledge in this area a wider use of high strength, light weight fibrous materials systems presently available is being impeded. Analytic solutions for single lap joints including the effects of transverse shear strains, normal strains and thermal strains have been included. Moreover, the methods include stress distribution throughout each adherend as well as the stresses in the adhesive bond. Using the methods an extensive parametric study was conducted to determine ways to maximize the strength under either static or fatigue loadings. Operational computer programs are available at both the University of Delaware and Convair Division of General Dynamics for the single lap joint.

The methods developed are presented in AFOSR TR-75-0125 August 1974, and published in the ASME Journal of Applied Mechanics April 1977.

In addition to the analytical research, an experimental program was conducted which concentrated on determining the effects of those parameters considered to be most influential on the static and fatigue life of an adhesive bonded single lap joint. These parameters include overlap length, adhesive thickness, laminate orientation, and the effect on the fatigue life whether or not the mean value of the fatigue load induces maximum stresses above or below the shear proportional limit of the adhesive material, wherein the analyses of stresses utilized the methods developed during this program.

Over and above determining experimentally the effect of the various parameters, and the obtainment of useful design information, it was hoped that the combined analytical program would provide considerable insight into the static and fatigue behavior of more complicated joints such as the double lap, the scarf, and stepped lap joints.

In this experimental program the adhesive was Hysol EA951 and the adherends consisted of seven laminae of 1002-S glass totalling a thickness of 0.063".

The failures experienced were primarily either cohesive or adhesive on the bond. The results of the static tests show that (1) the strongest bonded joint is one with large overlap (0.60" was the largest overlap tested at this time), with all 0° adherends of equal extensional stiffness, (2) the ultimate joint static

strength increases with increased overlap length, until finally the adherend is the critical failure component, (3) ply orientation in the adherends, or the ply immediately adjacent to the adhesive bond had only a minor influence on the static joint strength whenever failure occurred in the adhesive bond, and (4) adhesive thickness had a minimal influence on the joint strength.

In the first experimental program fifty-seven test pieces were utilized, twenty-nine with 0° uni-ply construction, and twenty-eight angle ply specimens with 45°/0°/-45°/0° repeated pattern. It was clearly evident from the test data that whenever the peak shear test in the adhesive at mean load was kept below the shear proportional limit, the fatigue life of the joint was markedly increased over joints whose peak adhesive stress at mean load was above the adhesive shear proportional limit. In the tests in which 100 lb. load increments were used, increases in life of the joint by factors of five or more were seen for those specimens in which runout ($= 4 \times 10^7$ cycles) was attained. Static tests subsequently performed on the fatigue specimens showed that the residual static strength was between 50% and 99% of the static ultimate strength of virgin specimens. Of the fatigue specimens which failed prior to four million cycles, all exhibited a cohesive-adhesive failure in the adhesive bond. Typically the failure surfaces displayed distinct bonds near the ends of the overlap length which were smooth indicating rubbing as the crack propagated inward, then a rougher central region characteristic of the failure surface of a static failure, indicating that eventually as the cracks propagated inwardly from each end, at some point the remaining adhesive area

was sufficiently small, and the stresses so high that instantaneous failure of the remaining bond line resulted. Therefore once a critical crack length was reached, a static failure occurred.

Other conclusions reached include the following: A 20% to 40% reduction in load carrying ability occurs in 4×10^7 cycles for specimens involving the angle ply construction compared to the uni-ply construction. To attain 4×10^7 cycles, a maximum load corresponding to 26% of the ultimate static strength can only be tolerated for a lap length of 0.30", and 20% for a lap length of 0.60", independent of ply orientation. There was no distinct effect of adhesive thickness on fatigue life.

Confirmation of the accuracy of the analytical methods developed in this research, termed BOND-3 and BOND-4, occurred in September 1974 when Sharpe and Muha presented their paper at an AMMRC Conference. Of twenty procedures compared the Renton-Vinson solutions came closest to the experimental stress distributions they obtained. Bond 4 enables one to determine accurately the stress field in both adhesive as well as each adherend for similar or dissimilar adherends of either isotropic or anisotropic materials. A laminated plate element is the building block for developing the method of analysis. The plate element used included provision for application of stress couple at each end, shear resultant and in-plane axial resultant at each end, plus normal distributed loads and surface shear loads on the upper and lower surface.

With the inclusion of transverse shear deformation and transverse normal strain and accurate shear stress and normal stress distribution in the adhesive is obtained. The shear stress is zero

at each edge of the overlap, reaches a maximum a short distance away from the edge and diminishes somewhat further in the interior of the single lap joint. Transverse normal stresses, sometimes termed peel stresses, reach a maximum tensile value at the edge of the overlap, and become compressive in the interior.

Later, additional experimental research included an extensive series of fatigue using the ductile Hysol EA951 adhesive, adherends made of the 1002-S glass-epoxy and Kevlar-49 epoxy, subjected to constant amplitude loads as before, but also to two-block, repeated spectrum loading. As before all constant amplitude fatigue tests were conducted at R = +.10 in tension. 124 glass adherend specimens were tested and 19 Kevlar-49 specimens were run.

The Kevlar-49 specimens which were all 0° uni-ply construction exhibited a generally "fuzzy failure surface". In the constant amplitude fatigue tests, the Kevlar-49 specimens exhibited a superior fatigue performance than the glass adherend construction. This is expected from the analytical predictions because the greater stiffness of the Kevlar-49 adherend material results in a lower maximum stress in the adhesive compared to the lower stiffness of the 1002-S glass adherends.

In the two-block repeated spectrum tests, the loading was changed every 50,000 cycles. Also the loading sequence effects were investigated. One series of tests used the previous mode, R = +.10 for the low load block, and varied only the mean load to obtain the high load block, which had R = +0.38. Another series of tests varied only the alternating load. The stress ratio was

again varied between +0.10 and +0.38. One of the objectives of this section was to test the hypothesis that the fatigue life of an adhesive under a two-block repeated loading spectrum can be described by a two parameter expression composed of the number of cycles at the high stress level, α, a stress interaction factor, $R^{1/a}$, where R is the ratio of fracture toughness at the lower load level to the higher load level and is a function of α. a is an experimentally determined constant. The expression is

$$N_g = \frac{N_1}{\alpha+R^{1/a}(1-\alpha)}$$

where N_g is the fatigue life of the test piece under the complex load history and N_1 is the fatigue life of the test piece at the maximum load level of the constant amplitude tests for R = +0.10. This criteria was developed by Liu and Corten, and their hypothesis assumes that damage is done at both load levels, but that more damage is done at the higher load level.

The experimental data indicates that when considering the mean load level variation effect only the specimens showed an increase in fatigue life under the two block loading spectrum compared to the constant amplitude fatigue only.

The results of the other loading sequence, in which only the alternating load was varied results in a reduction in fatigue life especially for the high to low load sequence.

In all cases the specimens failed in a manner analogous to the constant amplitude results. Also the Liu-Corten two parameter fatigue theory was found to have promise in predicting the fatigue life for a two-block loading spectrum.

In a comprehensive analytical parametric study to assess what is efficient design in single lap bonded joints, the objective is clearly to minimize edge shear resultants, minimize stress couples, and of course minimize peak stresses in the adhesive for a given load. The design recommendations are to always join adherends with identical extensional stiffnesses, A_{11}, and bending stiffnesses, D_{11}, regardless of their material system. Also, the quantity Q_{11}, should always be as large as possible for a given adhesive system. The overlap length should be approximately ten times, but not larger than ten times, the thickness of the minimum thickness adherend. Adhesives with low shear modulus are very preferable, if the ultimate shear stresses are comparable.

Other ways to improve the efficiency of single lap joints in metallic structures are to taper the adherends, and to introduce grooves normal to the load direction over half or over all of the overlap length. Any of these procedures increases the joint efficiency over the untapered-ungrooved construction.

More recently a new plane strain analytical solution for symmetric, anisotropic laminated plates subjected to thermal, moisture and mechanical loadings including surface tractions has been developed. This provides the wherewithal to investigate bonded joints including hygrothermal effects. Thus, the earlier Renton-Vinson methods developed on BOND-3 and BOND-4 will be replaced by this Wetherhold-Vinson model.

Currently, methods of analysis are being developed for single lap joints, double lap joints, single doublers, multiple doublers, and stepped lap joints. These methods will be completed

under the sponsorship of the Office of Naval Research.

Most recently a series of static and fatigue experiments were conducted involving single lap joints with graphite-epoxy adherends and two promising adhesive systems, after the best pieces were stored in an hygrothermal environment of 212°F, and 100% Relative Humidity for 1, 2, 3 and 7 months. Such a time-temperature-humidity environment was so severe that it was not possible to obtain meaningful test or design data. The tests were discontinued.

The above research has been published in 3 AFOSR Technical Reports, the Journal of Engineering Fracture Mechanics, AIAA Journal of Aircraft, AMMRC-MS-74-8, Journal of Adhesion, the ASME Journal of Applied Mechanics, the Ph.D. Dissertation of W. J. Renton, the Master's Thesis of R. C. Wetherhold, and presented at the 15th and 16th AIAA/ASME/SAE SDM Meetings, the U.S. Army Symposium on Solid Mechanics, the 4th U.S. Army Materials Technology Conference, and the ASTM Fourth Conference on Composite Materials.

D. Measurement of Shear Properties of Adhesives

Early in the program a major effort was initiated to accurately measure the shear mechanical properties of various adhesives, in order to insert the modulus properties into the analytical procedures developed to determine accurately the stresses in the adhesive and compare those with the proportional limit stresses and/or ultimate shear stresses.

The test piece developed involved 0.5" adherends of 1002-S glass-epoxy, 1" wide and 8" long. In this configuration the adherends are essentially rigid bodies compared to the thin relatively flexible adhesive material. Hence, for all practical purposes the

shear stress over the adhesive lap length is essentially constant, thus $\tau = P/A$, and the normal or peel stresses are for all practical purposes zero.

Early tests showed that the shear modulus of Hysol EA951 increased with increased adhesive thickness. One explanation for this is that flaws are more critical in a thinner adhesive. Whether the adherends are uni-ply or angle ply had a minimal influence on the adhesive shear modulus. Increased lap length results in a decrease in adhesive shear modulus. None of the above parameter variations affected the proportional limit of the adhesive.

More recently, shear property measurements were made for nineteen promising adhesives using the shear specimen developed during this program. Both room temperature properties and those at 212°F were obtained. Tests were repeated at least three times and in one case seventeen experiments were duplicated. Values of ultimate shear strength had standard deviations considerably less than 10% of mean values, even though failures were either cohesive or adhesive. At room temperature the strongest adhesives are the Hysol EA9628 and the Hysol ADX-663, while the weakest is the Atlas Epoxy Bond Paste. The stiffest by far is the Adhesive Engineering Aerobond 2143 adhesive, while the most flexible is the Cavalon 3000. The most durable adhesive is the Mobay Mondus CB-75, and the most brittle is the Atlas Amphesive 801.

At 212°F the strongest adhesives, again, are the Hysol ADX-663 and the Hysol EA9628. The most stiff and most brittle is again the Adhesive Engineering Aerobond 3000. The 3M AF-147 was the most flexible and most ductile. The adhesive with the largest

strain energy to failure is the Hysol ADX-663.

This research has been published in the Journal of Engineering Fracture Mechanics, ASTM Special Technical Publication 580, and the AIAA Journal of Aircraft.

E. Hygrothermal Effects

Recently, it has been agreed that the hygroscopic nature of polymeric systems, such as non-metallic matrix systems require that dilatations induced by the absorption of moisture be considered in the stress analysis of composite structures. Reduction in both strength and constitutive properties result from a hygrothermal environment.

A unified treatment of the hygrothermal effect has been developed as part of this research program. The methods developed employ effective moisture in-plane stress resultants and stress couples, which when added to mechanical and thermal loads, determine stresses resulting the total hygrothermal and mechanical loading environment.

The most important conclusion is that hygrothermal stresses are identically analogous to thermal stresses. The effect is dilatational. There exist coefficients of hygroscopic expansion analogous to coefficients of thermal expansion, and the hygrothermal stress are self equilibrating across the laminate thickness. Almost all analytical methods available today for composite structures should be modified to include hygrothermal effects because of their importance. Hence, the present research on developing methods of analysis for bonded joints includes hygrothermal effects. This basic research has been published in the Journal of Composite Materials, and as discussed in the next Section.

F. Analysis of Plates of Composite Materials

Early in the program, accurate complete methods of analyses were developed by Smith and Vinson to determine the buckling loads of composite material plates with various boundary conditions at room temperature.

More recently these methods have been modified to include hygrothermal effects so that buckling loads can be determined at any temperature and humidity conditions.

A general buckling theory has been formulated which accounts for the hygrothermal effects due to moisture diffusion and heating on one side, and on both sides of the plate in addition to including the effects of transverse shear and normal deformation as well as the bending-extensional coupling exhibited by generally laminated composite plates.

Furthermore a parametric study was conducted for a symmetric T300/S208 graphite epoxy plate for both simply supported and clamped boundary conditions for both steady state and transient hygrothermal conditions to show the deleterious effects of an hygrothermal environment. Also it was shown that for typical laminates of GY70/339 graphite epoxy, clamped, at elevated temperatures transverse shear deformation and normal deformation must be included to obtain accurate values of building loads.

In all cases, hygrothermal effects cannot be neglected in determining accurate values of buckling loads.

Lastly, accurate methods of analysis have been developed to determine stresses and deformations in plates of composite materials under lateral loads and a hygrothermal environment. Minimum potential energy theory was utilized, as well as the

inclusion of transverse shear and transverse normal deformation. Both clamped and simply-supported boundary conditions are studied, as well as various in-plane boundary conditions.

Thus this research results in accurate inclusive methods of analyses for all rectangular panels of composite materials for in-plane and lateral mechanical loads and hygrothermal loads to determine stresses, deformation and buckling stresses-complete.

The results have been published in 3 AFOSR Technical Reports, 3 Master's Theses, and presented at the 8th National Congress of Applied Mechanics and the 1978 ASME Winter Annual Meeting.

III. PUBLICATIONS

Research Papers

1. "Response of Spherical Shells of Composite Materials to Localized Loads", with H. S. Kliger; presented at the ASME Pressure Vessel and Piping-Nuclear-Materials Conference, Miami, June 1974; published in the ASME Journal of Pressure Vessel Technology, Vol. 96, Series J., No. 4, pp. 305-312, November 1974.

2. "On the Behavior of Bonded Joints in Composite Material Structures", with W. J. Renton, Journal of Engineering Fracture Mechanics, Vol. 7, pp. 41-60, 1975.

3. "Fatigue Behavior of Bonded Joints in Composite Material Structures", with W. J. Renton; presented at the 15th ASME/AIAA/SAE Structures, Structural Dynamics and Materials Conference, Las Vegas, April 1974, AIAA Preprint 74-383; published with the AIAA Journal of Aircraft, Vol. 12, No. 5, pp. 442-447, May 1975.

4. "Shear Property Measurements of Adhesives in Composite Material Bonded Joints", with W. J. Renton; presented at the ASTM Composite Reliability Conference, Las Vegas, April 1974; published in ASTM Special Technical Publication 580, pp. 119-132, 1975.

5. "Fatigue Response of Anisotropic Adherends Bonded Joints", with W. J. Renton; presented at the Army Symposium on Solid Mechanics, Cape Cod, September 1974; published in the Proceedings of the Symposium, AMMRC-MS-74-8, September 1974.

6. "The Efficient Design of Adhesive Bonded Joints", with W. J. Renton; presented at the 16th AIAA/ASME/SAE Structures, Structural Dynamics and Materials Conference, Denver, May 1975, AIAA Paper 75-798; published in the Journal of Adhesion, Vol. 7, pp. 175-193, 1975.

7. "Interlaminar Stresses in Laminated Cylindrical Shells of Composite Material" with T. L. Waltz; presented at the 16th AIAA/ASME/SAE Structures, Structural Dynamics and Materials Conference, Denver, May 1975, AIAA Paper 75-755; published in the AIAA Journal, Vol. 14, No. 9, pp. 1213-1218, September 1976.

8. "Stresses in Circular Cylindrical Shells of Composite Materials Subjected to Localized Loads", with H. S. Kliger and G. Z. Forristall; presented at the 12th Annual Meeting of the Society of Engineering Science, Austin, October 1975; to be published in the Transaction of the Conference.

9. "On Improvement in Structural Efficiency of Single Lap Bonded Joints", with W. J. Renton and J. Pajorowski; presented at the Fourth Army Materials Technology Conference - Advances in Joining Technology, Boston, September 1975; to be published in the Transactions of the Conference.

10. "On the Hygrothermal Response of Laminated Composite Systems", with R. B. Pipes and T. W. Chou; presented at the 17th AIAA/ASME/SAE Structures, Structural Dynamics and Materials Conference, Valley Forge, May 1976; published in the Journal of Composite Materials, pp. 130-148, April 1976.

11. "An Analytical Model for Bonded Joint Analysis in Composite Structures Including Hygrothermal Effects", with R. C. Wetherhold; presented at the ASTM Fourth Conference on Composite Materials, Valley Forge, May 1976.

12. "Analysis of Adhesively Bonded Joints Between Panels of Composite Materials", with W. J. Renton; published in the ASME Journal of Applied Mechanics, pp. 101-106, April 1977.

13. "Shear Properties of Promising Adhesives for Bonded Joints in Composite Material Structures", with D. L. Flaggs; presented at the 18th AIAA/ASME Structures, Structural Dynamics and Materials Conference, San Diego, March 1977, AIAA Preprint 77-419; accepted for publication in the AIAA Journal of Aircraft.

14. "Hygrothermal Effects on the Buckling of Laminated Composite Plates", with D. L. Flaggs; presented at the Eighth U. S. National Congress of Applied Mechanics, San Diego, June 1978; submitted for publication.

15. "The Behavior of Rectangular Composite Material Plates Under Lateral and Hygrothermal Loads", with J. G. Sloan; accepted for presentation at the 1978 ASME Winter Annual Meeting, December 1978.

AFOSR Technical Reports

16. "The Analysis and Design of Anisotropic Bonded Joints, Report No. 2", with W. J. Renton, AFOSR TR-75-0125, August 1974.

17. "The Effect of Transverse Shear Deformation on the Elastic Stability of Plates of Composite Materials", with A. P. Smith, AFOSR TR 75-1628, March 1975.

18. "Interlaminar Stresses in Laminated Cylindrical Shells of Composite Materials", with T. L. Waltz, AFOSR TR 75-1629, January 1975.

19. "The Effects of Relative Humidity and Elevated Temperatures on Composite Structures", with W. J. Walker, R. B. Pipes and D. R. Ulrich, AFOSR TR 77-0030, February 1977.

20. "Elastic Stability of Generally Laminated Composite Plates Including Hygrothermal Effects", with D. L. Flaggs, submitted for TR number, July 1977.

21. "An Analytical Model for Bonded Joint Analysis in Composite Structures Including Hygrothermal Effects", with R. C. Wetherhold, submitted to AFOSR for approval.

22. "On the State of Technology Regarding the Use of Mechanical Fasteners in Composite Material Structures", submitted to AFOSR for approval.

23. "The Behavior of Rectangular Composite Material Plates Under Lateral and Hygrothermal Loads", with J. G. Sloan, July 1978, submitted to AFOSR for approval.

24. "The Analyses and Design of Composite Material Bonded Joints Report No. 3", with W. J. Renton and D. L. Flaggs, July 1978, submitted to AFOSR for approval.

Ph.D. In Applied Science Graduates

25. Renton, W. James, "The Analysis and Design of Composite Material Bonded Joints Under Static and Fatigue Loadings", 1974. Dr. Renton is currently in charge of all composite material research and development for the Vought Corporation, Dallas, Texas.

Master of Mechanical and Aerospace Engineering Graduates

26. Waltz, Terence L., "Interlaminar Stresses in Laminated Cylindrical Shells of Composite Materials", 1975. Since graduation, Mr. Waltz has been working in composite materials research and development at Allegheny Ballistics Laboratory of Hercules, Inc.

27. Wetherhold, Robert C., "An Analytical Model for Bonded Joint Analysis in Composite Structures Including Hygrothermal Effects", 1976. Mr. Wetherhold is an engineer with the E. I. duPont deNemours and Company.

28. Flaggs, Donald L., "Elastic Stability of Generally Laminated Composite Plates Including Hygrothermal Effects", 1978. Mr. Flaggs is a research engineer with the Lockheed Palo Alto Laboratories working with Dr. Crossman in composite materials.

29. Sloan, James G., "The Behavior of Rectangular Composite Material Plates Under Lateral and Hygrothermal Loads", 1979. Mr. Sloan is an equipment engineer with Hercules, Inc.

IV. MISCELLANEOUS

In March, 1976, the AFOSR sponsored a National Conference on "The Effects of Relative Humidity and Elevated Temperatures on Composite Structures", at the University of Delaware, co-directed by Drs. Vinson and Pipes. The meeting included some ninety applied mechanics specialists and polymer chemists, evenly divided, who attended by invitation only.

Dr. Vinson was also chairman of a National ASTM Symposium on Environmental Effects on Advanced Composite Materials held in Dayton, Ohio on 29-30 September 1977. He will be Editor of the ASTM Special Technical Publication to be published later in 1978.

Dr. Vinson is the recipient of the 1977 Office of Naval Research-American Institute of Aeronautics and Astronautics Research Award in Structural Mechanics. It was awarded largely for his research in the area of the behavior of bonded joints in composite materials and structures. The award consists of a beautiful AIAA medal and plaque, and a $30,000 ONR research grant.